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# Optimal rates for plug-in estimators of density level sets

PHILIPPE RIGOLLET <sup>\*</sup>      and      RÉGIS VERT <sup>†</sup>

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## Abstract

In the context of density level set estimation, we study the convergence of general plug-in methods under two main assumptions on the density for a given level  $\lambda$ . More precisely, it is assumed that the density (i) is smooth in a neighborhood of  $\lambda$  and (ii) has  $\gamma$ -exponent at level  $\lambda$ . Condition (i) ensures that the density can be estimated at a standard nonparametric rate and condition (ii) is similar to Tsybakov's margin assumption which is stated for the classification framework. Under these assumptions, we derive optimal rates of convergence for plug-in estimators. Explicit convergence rates are given for plug-in estimators based on kernel density estimators when the underlying measure is the Lebesgue measure. Lower bounds proving optimality of the rates in a minimax sense when the density is Hölder smooth are also provided.

**Mathematics Subject Classifications:** Primary 62G05, Secondary 62C20, 62G05, 62G20.

**Key Words:** Density level sets, plug-in estimators, rates of convergence, kernel density estimators, minimax lower bounds.

**Short title:** Plug-in density level set estimation.

## 1 Introduction

Let  $Q$  be a positive  $\sigma$ -finite measure on  $\mathcal{X} \subseteq \mathbb{R}^d$ . Consider i.i.d random vectors  $(X_1, \dots, X_n)$  with distribution  $P$ , having an unknown probability

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density  $p$  with respect to the measure  $Q$ . For a fixed  $\lambda > 0$ , we are interested in the estimation of the  $\lambda$ -level set of the density  $p$ :

$$\Gamma_p(\lambda) \triangleq \{x \in \mathcal{X} : p(x) > \lambda\} . \quad (1.1)$$

Throughout the paper we fix  $\lambda > 0$  and when no confusion is possible we use the notation  $\Gamma(\lambda)$  or simply  $\Gamma$  instead of  $\Gamma_p(\lambda)$ . When  $Q$  is the Lebesgue measure on  $\mathbb{R}^d$ , density level sets typically correspond to minimum volume sets of given  $P$ -probability mass, as shown in Polonik (1997).

**Remark 1.1** *A somewhat preponderant definition of a density level set is*

$$\bar{\Gamma}(\lambda) \triangleq \{x \in \mathcal{X} : p(x) \geq \lambda\} \quad (1.2)$$

*that is the union of  $\Gamma(\lambda)$  and of the set  $\{x \in \mathcal{X} : p(x) = \lambda\}$ . Since in this paper the density is allowed to have flat parts at level  $\lambda$ , the sets  $\Gamma(\lambda)$  and  $\bar{\Gamma}(\lambda)$  can differ by an arbitrarily large set. Density level sets defined by (1.1) or by (1.2) can be estimated using plug-in estimators with positive or negative offset respectively (see Remark 2.1). However, definition (1.1) remains consistent the definition of the support of the density when  $\lambda = 0$ . The results detailed hereafter pertain only to this definition but are applicable to definition (1.2) after minor changes.*

Here are two possible applications of density level set estimation.

**Anomaly detection:** the goal is to detect an abnormal observation from a sample (see for example Steinwart et al., 2005, and references therein). One way to deal with that problem is to assume that abnormal observations do not belong to a group of concentrated observations. In this framework, observations are considered as abnormal when they do not belong to  $\Gamma(\lambda)$  for some fixed  $\lambda \geq 0$ . The special case  $\lambda = 0$ , which corresponds to support estimation has been examined by Devroye and Wise (1980). In the general case,  $\lambda$  can be considered as a tolerance level for anomalies: the smaller  $\lambda$ , the fewer observations are considered as being abnormal.

**Unsupervised or semi-supervised classification:** these two problems amount to identify areas where the observations are concentrated with possible use of some available labels for the semi-supervised case. For instance, it can be assumed that the connected components of  $\Gamma(\lambda)$ , for a fixed  $\lambda$ , are clusters of homogeneous observations as described in Hartigan (1975). Note that this definition has been refined for example in Stuetzle (2003).

**Remark 1.2** *In both applications, the choice of  $\lambda$  is critical and has to be addressed carefully. However, this problem is beyond the scope of this paper.*

There are essentially two approaches towards estimating density level sets from the sample  $(X_1, \dots, X_n)$ . The most straightforward is to resort to *plug-in* methods where the density  $p$  in the expression for  $\Gamma_p(\lambda)$  is replaced by its estimate computed from the sample. Another way to estimate density level sets is to resort to *direct* methods which are based on empirical excess-mass maximization. The *excess-mass*  $H$  is a functional that measures the quality of an estimator  $\hat{G}$  and is defined as follows (Hartigan, 1987; Müller and Sawitzki, 1987):

$$H(\hat{G}) = P(\hat{G}) - \lambda Q(\hat{G}) .$$

Excess-mass measures how the  $P$ -probability mass concentrates in the region  $\hat{G}$ , and it is maximized by  $\Gamma = \Gamma(\lambda)$ . Hence, it acts as a risk functional in the density level set estimation (DLSE) framework and it is natural to measure the performance of an estimator  $\hat{G}$  by its *excess-mass deficit*  $H(\Gamma) - H(\hat{G}) \geq 0$ . Further justifications for the well-foundedness of the excess mass criterion can be found in Polonik (1995). Recently, Gayraud and Rousseau (2005) proposed a Bayesian approach to DLSE together with interesting comparative simulations.

While local versions of direct methods have been deeply analyzed and proved to be optimal in a minimax sense, over a certain family of well-behaved distributions (see Tsybakov, 1997) and although reasonable implementations have been recently proposed (see for instance Steinwart et al., 2005), they are still not very easy to use for practical purposes, compared to plug-in methods. Indeed, in practice, rather than specifying a value for  $\lambda$ , the user can specify a value for  $\alpha$ , the  $P$ -probability mass of the level set. In this case, the value of  $\lambda$  is implied by that of  $\alpha$  and efficient direct methods can be derived (Scott and Nowak, 2006). However, in general, using direct methods, one has to run an optimization procedure several times, one for different density level values, then choose a posteriori the most suited level according to the desired rejection rate. Plug-in methods do not involve such a complex process: the density estimation step is only performed once and the construction of a density level set estimate simply amounts to thresholding the density estimate at the desired level.

On the other hand, in the related context of binary classification where more theoretical advances have been developed, the different analysis proposed so far have mainly supported a belief in the superiority of direct

methods. Yang (1999) shows that, under general assumptions, plug-in estimators cannot achieve a classification error risk convergence rate faster than  $O(1/\sqrt{n})$  (where  $n$  is the size of the data sample), and suffer from the curse of dimensionality. In contrast to that, under slightly different assumptions, direct methods achieve this rate  $O(1/\sqrt{n})$  whatever the dimensionality (see e.g. Vapnik, 1998; Devroye et al., 1996; Tsybakov, 2004b), and can even reach faster convergence rates- up to  $O(1/n)$ - under *Tsybakov's margin assumption* (see Mammen and Tsybakov, 1999; Tsybakov, 2004b; Tsybakov and van de Geer, 2005; Tarigan and van de Geer, 2006). This contributed to raising some pessimism concerning plug-in methods. Nevertheless such a comparison between plug-in methods and direct methods is far from being legitimate, since the aforementioned analyzes of both plug-in methods and direct ones have been carried out under the different sets of assumptions (those sets are not disjoint, but none of them is included in the other).

Recently, in the standard classification framework, Audibert and Tsybakov (2007) have combined a new type of assumption dealing with the smoothness of the *regression function* and the well known margin assumption. Under these assumptions, they derive fast convergence rates- even faster than  $O(1/n)$  in some situations- for plug-in classification rules based on local polynomial estimators. This new result reveals that plug-in methods should not be considered as inferior to direct methods and, more importantly, that this new type of assumption on the regression function is a critical point in the general analysis of classification procedures.

In this paper we extend such positive results to the DLSE framework: we revisit the analysis of plug-in density level set estimators, and show that they can be also very efficient under smoothness assumptions on the underlying density function  $p$ . Unlike the global smoothness assumption used in Audibert and Tsybakov (2007), the local smoothness assumption introduced here emphasizes the predominant role of the smoothness close to the level  $\lambda$  as opposed to the smoothness for values of  $p$  far from the level under consideration. Related papers are Baíllo et al. (2001) and Baíllo (2003), who investigate plug-in estimators based on a certain type of kernel density estimates. Baíllo et al. (2001) also study the convergence for the symmetric difference under other assumptions and Baíllo (2003) derives almost sure rates of convergence for a quantity different from the one studied here. It is interesting to observe that she introduces a condition similar to the  $\gamma$ -exponent used here.

The particular case  $\lambda = 0$ , corresponds to estimation of the support of density  $p$  and is often applied to anomaly detection. Following the pioneer paper of Devroye and Wise (1980), this problem has received more attention

than the general case  $\lambda \geq 0$  and has been treated using plug-in methods for example by Cuevas and Fraiman (1997). Unlike the previously cited papers, we derive rates of convergence and prove that these rates are optimal in a minimax sense. However, we do not treat the case  $\lambda = 0$  for the which the rates are typically different than for  $\lambda > 0$  as pointed out by Tsybakov (1997) for example. The techniques employed in the present analysis need some refinements to be extended to this case.

A general plug-in approach has been studied previously by Molchanov (1998), where a result on the asymptotic distribution of the Hausdorff distance is given. In a recent paper, Cuevas et al. (2006) study general plug-in estimators of the level sets. Under very general assumptions they derive consistency with respect to the Hausdorff metric and the measure of the symmetric difference. However, this very general framework does not allow them to derive rates of convergence.

This paper is organized as follows. Section 2 introduces the notation and definitions. Section 3 presents the main result, that is a new bound on the error of plug-in estimators based on general density estimators that satisfy a certain exponential inequality. We then apply, in Section 4, this result to the particular case of kernel density estimators, under the assumption that the underlying density belongs to some locally Hölder smooth class of densities. Finally, minimax lower bounds are given in Section 5, as a way to assess the optimality of the upper bounds involved in the main result.

## 2 Notation and Setup

For any vector  $x \in \mathbb{R}^d$ , denote by  $x^{(j)}$  its  $j$ th coordinate,  $j = 1, \dots, d$ . Denote by  $\|\cdot\|$  the Euclidean norm in  $\mathbb{R}^d$  and by  $\mathcal{B}(x, r)$  the closed Euclidean ball in  $\mathcal{X}$  centered at  $x \in \mathcal{X}$  and of radius  $r > 0$ .

The probability and expectation with respect to the joint distribution of  $(X_1, \dots, X_n)$  are denoted by  $\mathbb{P}$  and  $\mathbb{E}$  respectively. For any function  $f : \mathbb{R}^d \rightarrow \mathbb{R}$ , we denote by  $\|f\|_\infty = \sup_{x \in \mathbb{R}^d} |f(x)|$  the sup-norm of  $f$  and by  $\|f\| = (\int_{\mathbb{R}^d} f^2(x) dx)^{1/2}$  its  $L_2$ -norm. Also, for any measurable function  $f$  on  $\mathcal{X}$  and any set  $A \subset \mathcal{X}$ , we write for simplicity  $\{x \in \mathcal{X} : f(x) \in A\} = \{f \in A\}$ . Throughout the paper, we denote by  $C$  positive constants that can change from line to line and by  $c_j$  positive constants that have to be identified. Finally,  $A^c$  denotes the complement of the set  $A$ .

## 2.1 Plug-in density level set estimators with offset

For a fixed  $\lambda > 0$ , the plug-in estimator of  $\Gamma(\lambda)$  is defined by

$$\hat{\Gamma}(\lambda) = \{x \in \mathcal{X} : \hat{p}_n(x) > \lambda\},$$

where  $\hat{p}_n$  is a nonparametric estimator of  $p$ . For example,  $\hat{p}_n$  can be a kernel density estimator of  $p$ ,

$$\hat{p}_n(x) = \hat{p}_{n,h}(x) = \frac{1}{nh^d} \sum_{i=1}^n K\left(\frac{X_i - x}{h}\right), \quad x \in \mathcal{X},$$

where  $K : \mathbb{R}^d \rightarrow \mathbb{R}$  is a suitably chosen kernel and  $h > 0$  is the bandwidth parameter. For reasons that will be made clearer later, we consider in this paper the family of *plug-in estimators with offset*  $\ell_n$ , denoted by  $\tilde{\Gamma}_{\ell_n}$  and defined as follows:

$$\tilde{\Gamma}_{\ell_n} = \tilde{\Gamma}_{\ell_n}(\lambda) = \hat{\Gamma}(\lambda + \ell_n) = \{x \in \mathcal{X} : \hat{p}_n(x) \geq \lambda + \ell_n\},$$

where  $\ell_n$  is a quantity that typically tends to 0 as  $n$  tends to infinity.

**Remark 2.1** *As mentioned in Remark 1.1, when the goal is to estimate the set  $\Gamma(\lambda)$ , the offset  $\ell_n$  is chosen to be positive whereas for  $\bar{\Gamma}$  it has to be chosen negative. The effect of such choices, is to ensure that the set  $\{p = \lambda\}$  is respectively removed or added to the standard plug-in estimator with high probability. The following counter example suggested by an anonymous referee demonstrates that standard plug-in estimators can fail to estimate consistently the set  $\{p = \lambda\}$ .*

*Assume that  $\mathcal{X} \subset \mathbb{R}$  and that the density  $p$  is such that  $p(x) = 1/2$  for all  $x \in [0, 1]$  and that  $p(x) < 1/2$  elsewhere. In this case, it is clear that  $\Gamma(1/2) = \emptyset$  and  $\bar{\Gamma}(1/2) = [0, 1]$ . Assume now that we have an estimator  $\hat{p}$  such that  $|\hat{p}(x) - p(x)| \leq \varepsilon$ , where  $\varepsilon > 0$  is arbitrary small. If  $\hat{p}(x) = 1/2 + \varepsilon$  for any  $x \in [0, 1]$ , then  $\hat{\Gamma}(1/2) \supset [0, 1]$  and it fails to estimate consistently  $\Gamma(1/2)$  as  $\varepsilon$  tends to 0. However,  $\tilde{\Gamma}_{\ell_n}$  with a positive offset  $\ell_n > \varepsilon$  can become consistent as shown in Section 3. Conversely, if  $\hat{p}(x) = 1/2 - \varepsilon$  for any  $x \in [0, 1]$ , then  $\hat{\Gamma}(1/2)$  is not a consistent estimator of  $\bar{\Gamma}(1/2)$  but  $\tilde{\Gamma}_{\ell_n}$  with a negative offset  $\ell_n < -\varepsilon$  can be one.*

*As a consequence, plug-in density level set estimators can match both definitions of density level sets (1.1) or (1.2) by simply changing the sign of the offset.*

## 2.2 Measures of performance

Recall that  $Q$  is a positive  $\sigma$ -finite measure on  $\mathcal{X}$  and define the measure  $\tilde{Q}_\lambda$  that has density  $|p(\cdot) - \lambda|$  with respect to  $Q$ . To assess the performance of a density level set estimator, we use the two pseudo-distances between two sets  $G_1$  and  $G_2 \subseteq \mathcal{X}$ :

- (i) The  $Q$ -measure of the symmetric difference between  $G_1$  and  $G_2$ :

$$d_\Delta(G_1, G_2) = Q(G_1 \Delta G_2).$$

- (ii) The  $\tilde{Q}_\lambda$ -measure of the symmetric difference between  $G_1$  and  $G_2$ :

$$d_H(G_1, G_2) = \tilde{Q}_\lambda(G_1 \Delta G_2) = \int_{G_1 \Delta G_2} |p(x) - \lambda| dQ(x).$$

The quantity  $d_\Delta(G_1, G_2)$  is a standard and natural way to measure the distance between two sets  $G_1$  and  $G_2$ . Note that for any measurable set  $G \subseteq \mathcal{X}$ , the excess-mass  $H(G)$  can be written

$$H(G) = \int_G (p(x) - \lambda) dQ(x).$$

Thus, we can rewrite,

$$\begin{aligned} H(\Gamma) - H(\hat{G}) &= \int_{\mathcal{X}} (\mathbb{I}_{\{p(\cdot) \geq \lambda\}}(x) - \mathbb{I}_{\hat{G}}(x)) (p(x) - \lambda) dQ(x) \\ &= \int_{\Gamma \Delta \hat{G}} |p(x) - \lambda| dQ(x) = d_H(\hat{G}, \Gamma). \end{aligned}$$

This explains the notation  $d_H$ .

The following definition allows us to link  $d_H$  to  $d_\Delta$ .

**Definition 2.1** *For any  $\lambda, \gamma \geq 0$ , a function  $f : \mathcal{X} \rightarrow \mathbb{R}$  is said to have  $\gamma$ -exponent at level  $\lambda$  with respect to  $Q$  if there exist constants  $c_0 > 0$  and  $\varepsilon_0 > 0$  such that, for all  $0 < \varepsilon \leq \varepsilon_0$ ,*

$$Q \{x \in \mathcal{X} : 0 < |f(x) - \lambda| \leq \varepsilon\} \leq c_0 \varepsilon^\gamma.$$

The assumption under which the underlying density has  $\gamma$ -exponent at level  $\lambda$  was first introduced by Polonik (1995). Its counterpart in the context of binary classification is commonly referred to as *margin assumption* (see Mammen and Tsybakov, 1999; Tsybakov, 2004b).



The exponent  $\gamma$  controls the slope of the function around level  $\lambda$ . When  $\gamma = 0$ , the condition holds trivially and when  $\gamma$  is positive, it constrains the rate at which the function approaches the level  $\lambda$ . A standard case corresponds to  $\gamma = 1$ , arising for instance in the case where the gradient of  $f$  has a coordinate bounded away from 0 in a neighborhood of  $\{f = \lambda\}$ .

We now show that the pseudo-distances  $d_\Delta$  and  $d_H$  are linked when the density  $p$  has  $\gamma$ -exponent at level  $\lambda$ . The following proposition is a direct consequence of Proposition 6.1.

**Proposition 2.1** *Fix  $\lambda > 0$  and  $\gamma \geq 0$ . If the density  $p$  has  $\gamma$ -exponent at level  $\lambda$  w.r.t  $Q$ , then for any  $L_Q > 0$ , there exists  $C > 0$  such that for any  $G_1, G_2$  satisfying  $Q(G_1 \triangle G_2) \leq L_Q$  we have*

$$d_\Delta(G_1, G_2) \leq Q(G_1 \triangle G_2 \cap \{p = \lambda\}) + C (d_H(G_1, G_2))^{\frac{\gamma}{1+\gamma}}.$$

Note that for any density level set estimator  $\hat{G}$ , it holds  $d_H(\hat{G}, \Gamma(\lambda)) = d_H(\hat{G}, \bar{\Gamma}(\lambda))$ . In other words, choice of the definition of the density level set will not affect the performance of an estimator when measured by its excess mass deficit. However, the distance  $d_\Delta$  is very sensitive to this choice as illustrated in Remark 2.1 and one has to resort to offsets to control the first term on the right hand side of the result in Proposition 2.1.

### 3 Fast rates for plug-in density level sets estimators with offset

The first theorem states that rates of convergence for plug-in estimators with offset can be obtained using exponential inequalities for the corresponding nonparametric density estimator  $\hat{p}_n$ . In what follows, smoothness in the neighborhood of the level under consideration is particularly important and we define this neighborhood as follows:

$$\mathcal{D}(\eta) = \{p \in (\lambda - \eta, \lambda + \eta)\}, \quad \eta > 0$$

In the sequel, we will always use plug-in estimators with the same offset and we write for simplicity  $\tilde{\Gamma}_{\ell_n} = \tilde{\Gamma}$ .

**Theorem 3.1** *Fix  $\lambda > 0, \Delta > 0$  and let  $\mathcal{P}$  be a class of densities on  $\mathcal{X}$ . Let  $\hat{p}_n$  be an estimator of the density  $p$  constructed from data arising from  $p \in \mathcal{P}$  and such that  $Q(\hat{p}_n \geq \lambda) \leq M$ , almost surely for some positive constant  $M$ . Assume that there exists positive constants  $\eta, c_1, c_2, c_3, c_4, c_\delta, c'_\delta, a$  and  $b$ , such that*

- for  $Q$ -almost all  $x \in \mathcal{D}(\eta)$  and for any  $\delta$  such that  $c_\delta n^{-a/2} < \delta < \Delta$ , we have

$$\sup_{p \in \mathcal{P}} \mathbb{P}(|\hat{p}_n(x) - p(x)| \geq \delta) \leq c_1 e^{-c_2 n^a \delta^2}, \quad n \geq 1, \quad (3.1)$$

- for  $Q$ -almost all  $x \in \mathcal{X} \setminus \mathcal{D}(\eta)$ , for any  $\delta$  such that  $c'_\delta n^{-b/2} < \delta < \Delta$ , we have

$$\sup_{p \in \mathcal{P}} \mathbb{P}(|\hat{p}_n(x) - p(x)| \geq \delta) \leq c_3 e^{-c_4 n^a \delta^2}, \quad n \geq 1. \quad (3.2)$$

Then if  $p$  has  $\gamma$ -exponent at level  $\lambda$  for any  $p \in \mathcal{P}$ , the plug-in estimator  $\tilde{\Gamma}$  with offset  $\ell_n = n^{-\nu}$  for some  $\nu > a/2$  satisfies

$$\sup_{p \in \mathcal{P}} \mathbb{E} \left[ d_H(\Gamma_p(\lambda), \tilde{\Gamma}) \right] \leq c_5 n^{-\frac{(1+\gamma)a}{2}}, \quad (3.3)$$

$$\sup_{p \in \mathcal{P}} \mathbb{E} \left[ d_\Delta(\Gamma_p(\lambda), \tilde{\Gamma}) \right] \leq c_6 n^{-\frac{\gamma a}{2}}, \quad (3.4)$$

for  $n \geq n_0 = n_0(\lambda, \eta, a, b, \varepsilon_0, c_\delta, c'_\delta)$  and where  $c_5 > 0$  and  $c_6 > 0$  depend only on  $c_1, c_2, c_3, c_4, M, a, b, \gamma$  and  $\lambda$ .

Before giving the proof of the theorem, we comment on its meaning. First note that the main consequence of (3.1) is that  $|\hat{p}_n(x) - p(x)|$  is of order  $n^{-a}$  with polynomially high probability up to some logarithmic factors for any  $x$  in the neighborhood  $\mathcal{D}(\eta)$ . That is  $\hat{p}_n$  is a good pointwise estimator of  $p$  in this neighborhood. Equation (3.2) is of the same flavor as (3.1) but in a weaker form. It entails that for  $x$  outside of  $\mathcal{D}(\eta)$ ,  $\hat{p}_n(x)$  is a consistent estimator of  $p(x)$  with a polynomial rate of order  $n^{-a \wedge b}$  up to a logarithmic factor that can be as slow as desired since  $b$  does not appear in the rates (3.3) or (3.4).

PROOF. Note first that the conditions of Proposition 2.1 are satisfied. Indeed,  $Q(\{\hat{p}_n \geq \lambda + \ell_n\} \triangle \{p \geq \lambda\}) \leq Q(\hat{p}_n \geq \lambda) + Q(p \geq \lambda) \leq M + \lambda^{-1}$  and we choose  $L_Q = M + \lambda^{-1}$ . Therefore, if we prove that

$$\mathbb{E} Q(\Gamma_p(\lambda) \triangle \tilde{\Gamma} \cap \{p = \lambda\}) \leq C n^{-\frac{\gamma a}{2}}, \quad (3.5)$$

then (3.4) follows as a direct consequence of (3.3), (3.5) and the result of Proposition 2.1 together with Jensen's inequality. We begin by proving (3.5). Remark that

$$\Gamma_p(\lambda) \triangle \tilde{\Gamma} \cap \{p = \lambda\} = \{\hat{p}_n \geq \lambda + \ell_n\} \cap \{p = \lambda\} \subset \{|\hat{p}_n - p| \geq \ell_n\} \cap \mathcal{D}(\eta).$$

Therefore by the Fubini Theorem and assumption (3.1),

$$\mathbb{E}Q(\Gamma_p(\lambda) \triangle \tilde{\Gamma} \cap \{p = \lambda\}) \leq Q\{p = \lambda\}e^{-c_2 n^a \ell_n^2} \leq Cn^{-\frac{\gamma a}{2}},$$

which proves (3.5).

To prove (3.3), we use the same scheme as in the proof of Audibert and Tsybakov (2007, Theorem 3.1). Recall that  $\tilde{\Gamma} \triangle \Gamma = (\tilde{\Gamma} \cap \Gamma^c) \cup (\tilde{\Gamma}^c \cap \Gamma)$ . It yields

$$\mathbb{E} \left[ d_H(\Gamma, \tilde{\Gamma}) \right] = \mathbb{E} \int_{\tilde{\Gamma} \cap \Gamma^c} |p(x) - \lambda| dQ(x) + \mathbb{E} \int_{\tilde{\Gamma}^c \cap \Gamma} |p(x) - \lambda| dQ(x).$$

Define two sequences

$$\ell_n^a = n^{-a/2} \quad \text{and} \quad \ell_n^b = \left( \frac{c_4 n^{a \wedge b}}{2(1 + \gamma)a \log n} \right)^{-1/2}.$$

Let  $n_0$  be a positive integer such that  $2\ell_n < \ell_n^a < \ell_n^b < \eta \wedge \varepsilon_0 \wedge \Delta$  and  $\ell_n^b > c'_\delta n^{-b/2}$  for all  $n \geq n_0$ . In the remainder of the proof, we always assume that  $n \geq n_0$ . Consider the following disjoint decomposition:

$$\tilde{\Gamma}^c \cap \Gamma = \{\hat{p}_n < \lambda + \ell_n, p > \lambda\} \subset A_1 \cup A_2 \cup A_3, \quad (3.6)$$

where,

$$\begin{aligned} A_1 &= \{\hat{p}_n < \lambda + \ell_n, \lambda < p \leq \lambda + \ell_n^a\}, \\ A_2 &= \{\hat{p}_n < \lambda + \ell_n, \lambda + \ell_n^a < p \leq \lambda + \ell_n^b\}, \\ A_3 &= \{\hat{p}_n < \lambda + \ell_n, p > \lambda + \ell_n^b\}. \end{aligned}$$

Observe that  $A_1 \subseteq \{0 < |p - \lambda| \leq \ell_n^a\}$ . It yield,

$$\mathbb{E} \int_{A_1} |p(x) - \lambda| dQ(x) \leq \ell_n^a Q(A_1) \leq c_0 (\ell_n^a)^{1+\gamma} = c_0 n^{-\frac{(1+\gamma)a}{2}}, \quad (3.7)$$

where in the last inequality we used the  $\gamma$ -exponent of  $p$ . Define  $J_n = \lfloor \log_2 \left( \frac{\ell_n^b}{\ell_n^a} \right) \rfloor + 2$ , where  $\lfloor y \rfloor$  denote the maximal integer that is strictly smaller than  $y > 0$ . Then, we can partition  $A_2$  into:

$$A_2 = \bigcup_{j=1}^{J_n} \mathcal{X}_j \cap A_2,$$

where

$$\mathcal{X}_j = \{\hat{p}_n < \lambda + \ell_n, \lambda + 2^{j-1} \ell_n^a < p \leq \lambda + 2^j \ell_n^a\} \cap \mathcal{D}(\eta \wedge \varepsilon_0),$$

where  $J_n = \lfloor \log_2 \left( \frac{\ell_n^b}{\ell_n^a} \right) \rfloor + 2$  so that the  $\mathcal{X}_j \cap A_2$  indeed form a partition of  $A_2$ . Hence,

$$\mathbb{E} \int_{A_2} |p(x) - \lambda| dQ(x) = \sum_{j=1}^{J_n} \mathbb{E} \int_{\mathcal{X}_j \cap A_2} |p(x) - \lambda| dQ(x). \quad (3.8)$$

Now since  $\ell_n \leq \ell_n^a/2$ , we have

$$\mathcal{X}_j \subset \{|\hat{p}_n - p| > 2^{j-2} \ell_n^a\} \cap \{|p(x) - \lambda| < 2^j \ell_n^a\}.$$

Using the Fubini Theorem and the previous inclusion, the general term of the sum in the right-hand side of (3.8) can be bounded from above by

$$2^j \ell_n^a \int_{\mathcal{D}(\eta \wedge \varepsilon_0)} \mathbb{P} [|\hat{p}_n(x) - p(x)| > 2^{j-2} \ell_n^a] \mathbb{1}_{\{0 < |p(x) - \lambda| < 2^j \ell_n^a\}} dQ(x).$$

Remark that for any  $j \leq J_n$ , we have  $2^{j-2} \ell_n^a \leq \ell_n^b \leq \Delta$ . Using now (3.1) and the fact that  $p$  has  $\gamma$ -exponent at level  $\lambda$ , we get

$$\begin{aligned} \mathbb{E} \int_{A_2} |p(x) - \lambda| dQ(x) &\leq c_0 c_1 \sum_{j \geq 1} \exp(-c_2 n^a (2^{j-2} \ell_n^a)^2) (2^j \ell_n^a)^{1+\gamma} \\ &\leq C(\ell_n^a)^{1+\gamma} = Cn^{-\frac{(1+\gamma)a}{2}}. \end{aligned} \quad (3.9)$$

We now treat the integral over  $A_3$  using the Fubini theorem and the fact that  $\ell_n \leq \ell_n^b/2$ . We obtain

$$\begin{aligned} \mathbb{E} \int_{A_3} |p(x) - \lambda| dQ(x) &\leq \sup_{\substack{G \subseteq \mathcal{X} \\ Q(G) \leq 1/\lambda}} \int_G |p(x) - \lambda| \mathbb{P} [|\hat{p}_n(x) - p(x)| > \ell_n^b/2] dQ(x) \\ &\leq 2c_3 \exp(-c_4 n^a (\ell_n^b/2)^2) \leq 2c_3 n^{-\frac{(1+\gamma)a}{2}}, \end{aligned} \quad (3.10)$$

where in the last inequality, we used the fact that

$$\ell_n^b \geq \left( \frac{c_4 n^a}{2(1+\gamma)a \log n} \right)^{-1/2}.$$

In view of (3.6), if we combine (3.7), (3.9) and (3.10), we obtain

$$\mathbb{E} \int_{\tilde{\Gamma}^c \cap \Gamma} |p(x) - \lambda| dQ(x) \leq Cn^{-\frac{(1+\gamma)a}{2}}.$$

In the same manner, it can be shown that for  $n \geq n_0$ ,

$$\mathbb{E} \int_{\tilde{\Gamma} \cap \Gamma^c} |p(x) - \lambda| dQ(x) \leq C n^{-\frac{(1+\gamma)a}{2}}.$$

The only difference with the part of the proof detailed above is that in the step that corresponds to proving the equivalent of (3.10), we use the assumption that  $Q(\hat{p}_n \geq \lambda) \leq M$ , a.s.  $\blacksquare$

**Remark 3.1** *It is sometimes the case, for some applications that  $\tilde{\Gamma}$  is required to be included in  $\Gamma$  with high probability. When the offset  $\ell_n$  is chosen sufficiently large, i.e. of order at least  $n^{-a/2}$ , it can be shown that the resulting performance of the density level set estimator is only altered by a logarithmic factor whereas it can be enforced that,*

$$\mathbb{E} Q(\tilde{\Gamma} \cap \Gamma^c) \leq C n^{-\alpha},$$

for any  $\alpha > 0$  (Rigollet, 2007). In other words,  $\tilde{\Gamma}$  is included in  $\Gamma$  with arbitrarily large probability.

## 4 Optimal rates for plug-in estimators with offset based on kernel density estimators

In the rest of this paper, we fix the measure  $Q$  to be the Lebesgue measure on  $\mathbb{R}^d$  denoted by  $\text{Leb}_d$ .

In this section, we derive exponential inequalities of the type (3.1) when the estimator  $\hat{p}_n$  is a kernel density estimator and the density  $p$  belongs to some Hölder class of densities. We begin by giving the definition of the Hölder classes of densities that we consider.

### 4.1 Hölder classes of densities

Fix  $\beta > 0$  and  $\lambda > 0$ . For any  $d$ -tuples  $s = (s_1, \dots, s_d) \in \mathbb{N}^d$  and  $x = (x_1, \dots, x_d) \in \mathcal{X}$ , we define  $|s| = s_1 + \dots + s_d$ ,  $s! = s_1! \dots s_d!$  and  $x^s = x_1^{s_1} \dots x_d^{s_d}$ . Let  $D^s$  denote the differential operator

$$D^s = \frac{\partial^{s_1 + \dots + s_d}}{\partial x_1^{s_1} \dots \partial x_d^{s_d}}.$$

For any real valued function  $g$  on  $\mathcal{X}$  that is  $\lfloor \beta \rfloor$ -times continuously differentiable at point  $x_0 \in \mathcal{X}$ , we denote by  $g_{x_0}^{(\beta)}$  its Taylor polynomial of degree  $\lfloor \beta \rfloor$  at point  $x_0$ :

$$g_{x_0}^{(\beta)}(x) = \sum_{|s| \leq \lfloor \beta \rfloor} \frac{(x - x_0)^s}{s!} D^s g(x_0).$$

Fix  $L > 0, r > 0$  and denote by  $\Sigma(\beta, L, r, x_0)$  the set of functions  $g : \mathcal{X} \rightarrow \mathbb{R}$  that are  $\lfloor \beta \rfloor$ -times continuously differentiable at point  $x_0$  and satisfy

$$|g(x) - g_{x_0}^{(\beta)}(x)| \leq L \|x - x_0\|^\beta, \quad \forall x \in \mathcal{B}(x_0, r).$$

The set  $\Sigma(\beta, L, r, x_0)$  is called  $(\beta, L, r, x_0)$ -*locally Hölder class* of functions. We now define the class of densities that are considered in this paper.

**Definition 4.1** Fix  $\beta > 0, L > 0, r > 0, \lambda > 0$  and  $\gamma \geq 0$ . Recall the  $\mathcal{D}(\eta)$  is the neighborhood defined by

$$\mathcal{D}(\eta) = \{p \in (\lambda - \eta, \lambda + \eta)\}, \quad \eta > 0$$

Let  $\mathcal{P}_\Sigma(\beta, L, r, \lambda, \gamma)$  denote the class of all probability densities  $p$  on  $\mathcal{X}$  for which there exists  $\eta > 0$  such that

- (i)  $p \in \Sigma(\beta, L, r, x_0)$  for all  $x_0 \in \mathcal{D}(\eta)$ , apart from a set of null Lebesgue measure  $\text{Leb}_d$ .
- (ii)  $\exists \beta' > 0$  such that  $p \in \Sigma(\beta', L, r, x_0)$ , for all  $x_0 \notin \mathcal{D}(\eta)$ , apart from a set of null measure  $\text{Leb}_d$ .
- (iii)  $p$  has  $\gamma$ -exponent at level  $\lambda$  with respect to the Lebesgue measure.
- (iv)  $p$  is uniformly bounded by a constant  $L^*$ .

The class  $\mathcal{P}_\Sigma(\beta, L, r, \lambda, \gamma)$  is the class of uniformly bounded (condition (iv)) densities that have  $\gamma$ -exponent at level  $\lambda$  with respect to  $\text{Leb}_d$  (condition (iii)) and that are smooth in the neighborhood of the level under consideration (condition (i)). Note that the parameters  $\beta'$  in condition (ii) and  $L^*$  in condition (iv) do not appear in the notation of the class. Indeed  $\beta' > 0$  can be arbitrary close to 0 and this will not affect the rates of convergence. Actually, the role of condition (ii) is to ensure that any density from the class can be consistently estimated at any point with an arbitrary slow polynomial rate. In the same manner, the constant  $L^*$  does

not appear in the rates of convergence and only affects the constants. Conditions (i) and (ii) are smoothness conditions that ensure consistency of the nonparametric density estimator used in the plug-in estimator. The class of densities  $\mathcal{P}_\Sigma = \mathcal{P}_\Sigma(\beta, L, r, \lambda, \gamma)$  is similar to the class of regression functions considered in Audibert and Tsybakov (2007). However, besides the additional assumption that functions in  $\mathcal{P}_\Sigma$  are probability densities, the main improvement here is that the regularity of a density in  $\mathcal{P}_\Sigma$  can be arbitrary low outside of a neighborhood of the level under consideration, yielding slower rates of pointwise estimation. We prove below (cf. Corollary 4.1) that optimal rates of convergence for DLSE are possible for this larger class of densities, which corroborates the idea that the density need not be precisely estimated far from the level  $\lambda$ .

The next proposition can be derived by following the lines of the proof of Proposition 3.4 (fourth item) of Audibert and Tsybakov (2005).

**Proposition 4.1** *If  $\gamma(\beta \wedge 1) > 1$ , either  $\Gamma$  has empty interior or its complement  $\Gamma^c$  does. Conversely, if  $\gamma(\beta \wedge 1) \leq 1$ , there exist densities such that both  $\Gamma$  and  $\Gamma^c$  have nonempty interior.*

## 4.2 Exponential inequalities for kernel density estimators

To estimate a density  $p$  from the class  $\mathcal{P}_\Sigma(\beta, L, r, \lambda, \gamma)$ , we can use a *kernel density estimator* defined by:

$$\hat{p}_n(x) = \hat{p}_{n,h}(x) = \frac{1}{nh^d} \sum_{i=1}^n K\left(\frac{X_i - x}{h}\right), \quad (4.11)$$

where  $h > 0$  is the bandwidth parameter and  $K : \mathcal{X} \rightarrow \mathbb{R}$  is a kernel. This choice is not the only possible one and all we need is an estimator that satisfies exponential inequalities as in (3.1) and (3.2). The following lemma states that it is possible to derive such exponential inequalities for a kernel density estimator with a  $\beta^*$ -valid kernel where  $\beta^* \geq \beta$ . The definition of  $\beta$ -valid kernel is recalled in the appendix, Definition 6.1 (see also Tsybakov, 2004b, for example).

**Lemma 4.1** *Let  $P$  be a distribution on  $\mathbb{R}^d$  having a density  $p$  w.r.t. the Lebesgue measure and such that  $\|p\|_\infty \leq L^*$  for some constant  $L^* > 0$ . Fix  $\beta > 0$ ,  $\beta^* \geq \beta$ ,  $L > 0$ ,  $r > 0$  and assume that  $p \in \Sigma(\beta, L, r, x_0)$ . Let  $\hat{p}_n$  be a kernel density estimator with bandwidth  $h > 0$  and  $\beta^*$ -valid kernel  $K$ , given an i.i.d. sample  $X_1, \dots, X_n$  from  $P$ . Set*

$$\Delta = \frac{6L^*\|K\|^2}{\|K\|_\infty + L^* + L \int \|t\|^\beta K(t) dt}.$$

Then, for all  $\delta, h \leq r$  such that  $\Delta > \delta > 2Lc_7h^\beta > 0$ , we have,

$$\mathbb{P}\{|\hat{p}_n(x_0) - p(x_0)| \geq \delta\} \leq 2 \exp\left(-c_8 n h^d \delta^2\right),$$

where  $c_7 = \int \|t\|^\beta K(t) dt$  and  $c_8 = 1/(16L^* \|K\|^2)$ .

PROOF. For any  $x_0 \in \mathbb{R}^d$ ,

$$|\hat{p}_n(x_0) - p(x_0)| = \frac{1}{n} \left| \sum_{i=1}^n Z_i(x_0) \right|,$$

with

$$Z_i(x) = \frac{1}{h^d} K\left(\frac{X_i - x}{h}\right) - p(x).$$

The expectation of  $Z_i(x_0)$  is the pointwise bias of a kernel density estimator with bandwidth  $h$ . Under the assumptions of the theorem, it is controlled in the following way

$$|\mathbb{E}Z_i(x_0)| \leq Lc_7h^\beta.$$

Indeed,

$$\begin{aligned} |\mathbb{E}Z_i(x_0)| &= \\ &= \left| \int \frac{1}{h^d} K\left(\frac{t}{h}\right) [p(x_0 + t) - p(x_0)] dt \right| \\ &= \left| \int K(t) [p(x_0 + ht) - p(x_0)] dt \right| \\ &= \left| \int K(t) [p(x_0 + ht) - p_{x_0}^{(\beta)}(x_0 + ht)] dt \right. \\ &\quad \left. + \int K(t) [p_{x_0}^{(\beta)}(x_0 + ht) - p(x_0)] dt \right|. \end{aligned} \tag{4.12}$$

To control the first term in the right hand side of (4.12), remark that since  $K$  has support  $[-1, 1]^d$ , for any  $h < r/\sqrt{d}$ , we have  $x_0 + ht \in \mathcal{B}(x_0, r)$  for any  $t \in [-1, 1]^d$ . Thus, using the fact that  $p$  is in  $\Sigma(\beta, L, r, x_0)$  we have

$$\left| \int K(t) [p(x_0 + ht) - p_{x_0}^{(\beta)}(x_0 + ht)] dt \right| \leq L \int |K(t)| \|ht\|^\beta dt.$$

Now, since  $K$  is a  $[\beta]$ -valid kernel (cf. Proposition 6.2) and  $p_{x_0}^{(\beta)} - p(x_0)$  is a polynomial of degree at most  $[\beta]$  with no constant term, the second term in the right hand side of (4.12) is zero. Therefore, it holds

$$|\mathbb{E}Z_i(x_0)| \leq Lh^\beta \int |K(t)| \|t\|^\beta dt, \quad \text{for any } h \leq r.$$



Now denote for simplicity  $Z_i = Z_i(x_0)$  and let  $\overline{Z}_i$  be the centered version of  $Z_i$ . Then, when  $Lc_7h^\beta \leq \delta/2$ ,

$$\begin{aligned} \mathbb{P}\{|\hat{p}_n(x_0) - p(x_0)| \geq \delta\} &\leq \mathbb{P}\left\{\frac{1}{n}\left|\sum_{i=1}^n \overline{Z}_i\right| \geq \delta - Lc_7h^\beta\right\} \\ &\leq \mathbb{P}\left\{\frac{1}{n}\left|\sum_{i=1}^n \overline{Z}_i\right| \geq \frac{\delta}{2}\right\}. \end{aligned}$$

The right-hand side of the last inequality can be bounded applying Bernstein's inequality (see Devroye et al., 1996, Theorem 8.4, p. 124) to  $\overline{Z}_i$  and  $-\overline{Z}_i$  successively. For  $h \leq 1$ , one has

$$|\overline{Z}_i| \leq \|K\|_\infty h^{-d} + L^* + Lc_7h^\beta \leq c_9h^{-d},$$

where  $c_9 = \|K\|_\infty + L^* + Lc_7$  and

$$\text{Var}\{Z_i\} \leq h^{-d} \int K(u)^2 p(x_0 + hu) du \leq c_{10}h^{-d},$$

where  $c_{10} = L^*\|K\|^2$ . Applying now Bernstein's inequality yields

$$\begin{aligned} \mathbb{P}\{|\hat{p}_n(x_0) - p(x_0)| \geq \delta\} &\leq 2 \exp\left(-\frac{n(\delta/2)^2}{2(c_{10}h^{-d} + c_9h^{-d}\delta/6)}\right) \\ &\leq 2 \exp\left(-c_8nh^d\delta^2\right), \end{aligned}$$

for any  $\delta \leq \Delta$  and where  $\Delta = 6c_{10}/c_9$  and  $c_8 = 1/(16c_{10})$ . ■

We can therefore apply Theorem 3.1. When the choice of  $h$  is optimal, i.e.,  $h = n^{-1/(2\beta+d)}$ , it yields the following corollary.

**Corollary 4.1** *Let the underlying measure  $Q$  be the Lebesgue measure on  $\mathbb{R}^d$ . Fix  $\beta > 0$ ,  $L > 0$ ,  $r > 0$ ,  $\lambda > 0$ ,  $\gamma > 0$  and consider the plug-in estimator  $\tilde{\Gamma}$  with offset  $\ell_n = n^{-\nu}$  for some  $\nu > \beta/(2\beta + d)$ . The nonparametric estimator  $\hat{p}_n$  is the kernel density estimator defined in (4.11) with bandwidth parameter  $h = n^{-1/(2\beta+d)}$  and  $\beta^*$ -valid kernel  $K$ , where  $\beta^* = \beta \vee \beta'$  and  $\beta'$  is the parameter from Definition 4.1. Then,*

$$\begin{aligned} \sup_{p \in \mathcal{P}_\Sigma(\beta, L, r, \lambda, \gamma)} \mathbb{E} \left[ d_H(\Gamma_p(\lambda), \tilde{\Gamma}) \right] &\leq c_{11}n^{-\frac{(1+\gamma)\beta}{2\beta+d}}, \\ \sup_{p \in \mathcal{P}_\Sigma(\beta, L, r, \lambda, \gamma)} \mathbb{E} \left[ d_\Delta(\Gamma_p(\lambda), \tilde{\Gamma}) \right] &\leq c_{12}n^{-\frac{\gamma\beta}{2\beta+d}}, \end{aligned}$$

where  $c_{11} > 0$  and  $c_{12} > 0$  depend on the constants  $c_7$  and  $c_8$  that appear in Lemma 4.1, on  $c_0, \beta, \beta', \gamma, d$  and on  $\lambda$ .

PROOF. The results are direct consequences of Theorem 3.1 when  $\hat{p}_n$  is chosen as in (4.11). We need to check that for such an estimator we have  $\text{Leb}_d(\hat{p}_n \geq \lambda) \leq M$ , almost surely for some  $M > 0$ . Note that since  $K \in L_1(\mathbb{R}^d)$ , we have

$$\infty > \int_{\mathbb{R}^d} |K(x)| d\text{Leb}_d(x) \geq \int_{\{\hat{p}_n \geq \lambda\}} |\hat{p}_n(x)| d\text{Leb}_d(x) \geq \lambda \text{Leb}_d\{\hat{p}_n \geq \lambda\}.$$

Hence, the condition is satisfied with  $M = \lambda^{-1} \int |K|$ . All the other conditions of Theorem 3.1 are satisfied and we can apply it with  $a = 2\beta/(2\beta + d)$  and  $b = 2\beta'/(2\beta + d)$ .  $\blacksquare$

## 5 Minimax lower bounds

The following theorem shows that the rates obtained in Corollary 4.1 are optimal in a minimax sense.

**Theorem 5.1** *Let the underlying measure  $Q$  be the Lebesgue measure on  $\mathbb{R}^d$ . Fix  $\lambda > 0$  and let  $L, r, \beta, \gamma$  be positive constants such that  $\gamma\beta \leq 1$ . Then, for any  $n \geq 1$  and any estimator  $\hat{G}_n$  of  $\Gamma_p(\lambda)$  constructed from the sample  $X_1, \dots, X_n$ , we have*

$$\begin{aligned} \sup_{p \in \mathcal{P}_{\Sigma}(\beta, L, r, \lambda, \gamma)} \mathbb{E} \left[ d_H(\Gamma_p(\lambda), \hat{G}_n) \right] &\geq C n^{-\frac{(1+\gamma)\beta}{2\beta+d}}, \\ \sup_{p \in \mathcal{P}_{\Sigma}(\beta, L, r, \lambda, \gamma)} \mathbb{E} \left[ d_{\Delta}(\Gamma_p(\lambda), \hat{G}_n) \right] &\geq C n^{-\frac{\gamma\beta}{2\beta+d}}. \end{aligned} \quad (5.1)$$

PROOF. In view of Proposition 2.1 and since we have  $\text{Leb}_d[\Gamma_p(\lambda)] \leq \lambda^{-1} < \infty$ , we only have to prove (5.1). To that end, we will use Lemma 6.2 with  $d = d_{\Delta}$ ,  $\varepsilon = \varepsilon_n \geq C n^{-\frac{\gamma\beta}{2\beta+d}}$  and  $\mathcal{P} = \mathcal{P}_{\Sigma}(\beta, L, r, \lambda, \gamma)$ . Thus our goal is to find a family  $\mathcal{N}$  of densities that are in  $\mathcal{P}$  such that the densities in  $\mathcal{N}$  are close to each other for the Kullback-Leibler divergence and yield density level sets that are far apart in terms of the pseudo-distance  $d_{\Delta}$ .

We now describe the construction of the family  $\mathcal{N}$ .

We can assume without loss of generality that  $\lambda = 1$ . Consider the integer  $q = \lfloor 33n^{\frac{1}{2\beta+d}} \rfloor$ , and the regular grid  $\mathcal{G}$  on  $[0, 1]^d$  defined as

$$\mathcal{G} = \left\{ \left( \frac{2k_1 + 1}{q}, \dots, \frac{2k_d + 1}{q} \right), k_i \in \{0, \dots, q-1\}, i = 1, \dots, d \right\}.$$

Denote by  $\{g_j\}_{1 \leq j \leq q^d}$  the elements of the grid, the choice of indexing being of no importance for what follows. Define the integer  $m = \lfloor q^{d-\gamma\beta}/4 \rfloor + 8$  so that  $8 \leq m \leq q^d/2$ . Let  $\mathcal{J} = \{1, 3, \dots, 2m-1\}$  be the set of odd integers between 1 and  $2m-1$  and for any  $j = 1, \dots, 2m$ , define the balls  $B_j = \mathcal{B}(g_j, \kappa)$ , where  $\kappa = 1/q$ . Set  $B_0 = [0, 1]^d \setminus \bigcup_{j=1}^{2m} B_j$ .

Let  $\phi_\beta : \mathbb{R}^d \rightarrow \mathbb{R}_+$  be a smooth function defined as follows. If  $\beta < 1$ , the function  $\phi_\beta$  is defined as:

$$\phi_\beta(x) = \begin{cases} C_\beta(1 - \|x\|)^\beta & \text{if } 0 \leq \|x\| \leq 1, \\ 0 & \text{if } \|x\| > 1. \end{cases}$$

If  $\beta \geq 1$ , the function  $\phi_\beta$  is defined as:

$$\phi_\beta(x) = \begin{cases} C_\beta(2^{1-\beta} - \|x\|^\beta) & \text{if } 0 \leq \|x\| \leq 1/2, \\ C_\beta(1 - \|x\|)^\beta & \text{if } 1/2 \leq \|x\| \leq 1, \\ 0 & \text{if } \|x\| > 1, \end{cases}$$

where in both cases,  $C_\beta > 0$  is chosen small enough to ensure that  $|\phi_\beta(x) - \phi_\beta(x')| \leq L\|x - x'\|^\beta$  for any  $x, x' \in \mathbb{R}^d$ .

Then, for any  $\omega = (\omega_1, \dots, \omega_m) \in \{0, 1\}^m$ , define the function on  $[0, 1]^d$

$$p_\omega(x) = 1 + \sum_{j \in \mathcal{J}} \omega_j [\varphi_j(x) - \varphi_{j+1}(x)],$$

where  $\varphi_j(x) = \kappa^\beta \phi([x - g_j]/\kappa) \mathbb{I}_{\{x \in B_j\}}$ .

Consider a subset  $\Omega \subset \{0, 1\}^m$  and define the family  $\mathcal{N}$  as

$$\mathcal{N} = \{p_\omega, \omega \in \Omega\},$$

where  $\omega_0 = (0, \dots, 0) \in \Omega$ . The set  $\Omega$ , will be chosen in order to fulfill the conditions of Lemma 6.2.

FIRST CONDITION:  $\mathcal{N} \subset \mathcal{P}_\Sigma(\beta, L, r, 1, \gamma)$ .

First, note that the constants  $C_\beta$  can always be adjusted so that  $\|\varphi_j\|_\infty \leq 1$  for any  $j$  so that for any  $\omega \in \Omega$ ,  $p_\omega$  is a density that satisfies  $\|p_\omega\|_\infty \leq 2$  and trivially  $p_\omega \in \Sigma(\beta, L, r, x_0)$ .

Therefore it remains to check that  $p_\omega$  has  $\gamma$ -exponent at level 1 with respect to the Lebesgue measure. We have

$$\begin{aligned} \text{Leb}_d(x : 0 < |p_\omega(x) - 1| \leq \varepsilon) &= 2 \sum_{j \in \mathcal{J}} \text{Leb}_d(x : 0 < |p_\omega(x) - 1| \leq \varepsilon, x \in B_j) \\ &\leq 2m \text{Leb}_d(x : 0 < \phi([x - g_1]/\kappa) \leq \varepsilon \kappa^{-\beta}) \\ &= 2m \int_{\mathcal{B}(0,1)} \mathbb{I}_{\{\phi(x/\kappa) \leq \varepsilon \kappa^{-\beta}\}} dx \end{aligned}$$

The last term in the previous system of equations is treated differently whether  $\beta < 1$  or  $\beta \geq 1$ . If  $\beta < 1$ , it holds

$$\begin{aligned}
2m \int_{\mathcal{B}(0,1)} \mathbb{I}_{\{\phi(x/\kappa) \leq \varepsilon \kappa^{-\beta}\}} dx &\leq C(m\kappa^d \mathbb{I}_{\{\varepsilon > \kappa^\beta\}} + m[\kappa^d - (\kappa - \varepsilon^{1/\beta})^d] \mathbb{I}_{\{\varepsilon \leq \kappa^\beta\}}) \\
&\leq C(\kappa^{\gamma\beta} \mathbb{I}_{\{\varepsilon^\gamma > \kappa^{\gamma\beta}\}} + m\kappa^{d-1} \varepsilon^{1/\beta} \mathbb{I}_{\{\kappa > \varepsilon^{1/\beta}\}}) \\
&\leq C(\varepsilon^\gamma + \kappa^{\gamma\beta-1} \varepsilon^{1/\beta} \mathbb{I}_{\{\kappa > \varepsilon^{1/\beta}\}}) \\
&\leq C\varepsilon^\gamma,
\end{aligned} \tag{5.2}$$

where we used the fact that  $\gamma\beta - 1 \leq 0$  to bound the second term in the last but one inequality

We now treat the case  $\beta > 1$ . Note that integration over  $x$  such that  $\|x\| \geq \kappa/2$  can be treated in the same manner as for the case  $\beta < 1$ . The integral over  $x$  such that  $\|x\| < \kappa/2$  is trivially upper bounded by a term proportional to the volume of the ball  $\mathcal{B}(0, \kappa/2)$ . It yields

$$\begin{aligned}
2m \int_{\mathcal{B}(0,1)} \mathbb{I}_{\{\phi(x/\kappa) \leq \varepsilon \kappa^{-\beta}\}} dx &\leq C(m\kappa^d \mathbb{I}_{\{\varepsilon > C_\beta(\kappa/2)^\beta\}} + m\kappa^{d-1} \varepsilon^{1/\beta} \mathbb{I}_{\{\varepsilon \leq C_\beta(\kappa/2)^\beta\}}) \\
&\leq C(\kappa^{\gamma\beta} \mathbb{I}_{\{\kappa \leq 2(\varepsilon/C_\beta)^{1/\beta}\}} + m\kappa^{d-1} \varepsilon^{1/\beta} \mathbb{I}_{\{\kappa > 2(\varepsilon/C_\beta)^{1/\beta}\}}) \\
&\leq C\varepsilon^\gamma,
\end{aligned} \tag{5.3}$$

SECOND CONDITION (6.3):  $d_\Delta(\Gamma_p, \Gamma_q) \geq \varepsilon_n, \forall p, q \in \mathcal{N}, p \neq q$ .

By construction, for any  $\omega, \omega' \in \{0, 1\}^m$ ,

$$d_\Delta(\Gamma_{p_\omega}, \Gamma_{p_{\omega'}}) = 2\text{Leb}_d(B_1) \sum_{j=1}^m \mathbb{I}_{\{\omega_j \neq \omega'_j\}} \geq C\kappa^d \sum_{j=1}^m \mathbb{I}_{\{\omega_j \neq \omega'_j\}}.$$

We need to bound from below the Hamming distance between  $\omega$  and  $\omega'$ , defined for any  $\omega, \omega' \in \Omega$  by

$$\rho(\omega, \omega') = \sum_{j=1}^m \mathbb{I}_{\{\omega_j \neq \omega'_j\}}.$$

To do so we use the Varshamov-Gilbert bound (cf. Lemma 6.1) that guarantees the existence of  $\Omega \ni \omega_0$  such that  $\text{card}(\Omega) \geq 2^{m/8}$  and  $\rho(\omega, \omega') \geq m/8$  for any  $\omega, \omega' \in \Omega$ . For such  $\Omega$  we have

$$d_\Delta(\Gamma_{p_\omega}, \Gamma_{p_{\omega'}}) \geq C m \kappa^d \geq C n^{-\frac{\gamma\beta}{2\beta+d}}.$$

THIRD CONDITION:  $\max_{\omega \in \Omega} K(p_\omega, p_{\omega_0}) \leq C \log(\text{card}(\mathcal{N}))$ .

Note that for the above choice of  $\Omega$ , we have  $\text{card}(\mathcal{N}) \geq 2^{m/8}$ . Therefore  $\log(\text{card}(\mathcal{N})) \geq Cm$  and we only have to prove that

$$\max_{\omega \in \Omega} K(p_\omega, p_{\omega_0}) \leq Cm.$$

Denote by  $\xi_j(x) = \varphi_j(x) - \varphi_{j+1}(x)$ . For any  $p_\omega \in \mathcal{N}$ , we have,

$$\begin{aligned} K(p_\omega, p_{\omega_0}) &= n \sum_{j \in \mathcal{J}} \int_{B_j \cup B_{j+1}} \log(1 + \omega_j \xi_j(x)) (1 + \omega_j \xi_j(x)) dx, \\ &\leq 2n \sum_{j \in \mathcal{J}} \int_{B_1} \omega_j^2 \varphi_1^2(x) dx, \\ &\leq 2nm\kappa^{(2\beta+d)} \int_{\mathcal{B}(0,1)} \phi^2(x) dx, \\ &\leq Cm, \\ &\leq C \log(\text{card}(\mathcal{N})), \end{aligned}$$

where in the first inequality we use the convexity inequality  $\log(1+x) \leq x$  together with the invariance by translation of the family  $\{\varphi_j\}_j$ .

We can therefore apply Lemma 6.2 and Theorem 5.1 is proved.  $\blacksquare$

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## 6 Appendix

Several results that can be omitted in a first reading are gathered in this appendix.

### 6.1 Equivalent formulation for the $\gamma$ -exponent condition

The following proposition gives an equivalent formulation for the  $\gamma$ -exponent condition.

**Proposition 6.1** *Fix  $\lambda > 0, \gamma > 0$  and  $L_Q > 0$ .*

*Define  $\mathcal{L} = \mathcal{L}(\lambda) = \{p = \lambda\}$ . The two following statements are equivalent.*

(i)  $\exists c > 0$  and  $\varepsilon_0 > 0$ , such that for any  $0 < \varepsilon \leq \varepsilon_0$ , we have

$$Q \{x \in \mathcal{X} : 0 < |p(x) - \lambda| \leq \varepsilon\} \leq c\varepsilon^\gamma.$$

(ii)  $\exists c' > 0$  and  $\varepsilon_1 > 0$ , such that for any  $0 < \varepsilon \leq \varepsilon_1$ , we have

$$Q \{x \in \mathcal{X} : 0 < |p(x) - \lambda| \leq \varepsilon\} \leq L_Q$$

and for all  $G \subseteq \mathcal{X} \setminus \mathcal{L}$  satisfying  $Q(G) \leq L_Q$ , we have

$$Q(G) \leq c' \left( \int_G |p(x) - \lambda| dQ(x) \right)^{\frac{\gamma}{1+\gamma}}. \quad (6.1)$$

PROOF. The proof of (i)  $\Rightarrow$  (ii) essentially follows that of Tsybakov (2004b, Proposition 1). Define

$$\varepsilon_1 = \varepsilon_0 \wedge \left( \frac{L_Q}{c(1+\gamma)} \right)^{1/\gamma}.$$

Observe that for any  $0 < \varepsilon \leq \varepsilon_1$ , we have

$$Q \{x \in \mathcal{X} : 0 < |p(x) - \lambda| \leq \varepsilon\} \leq c\varepsilon^\gamma \leq c\varepsilon_1^\gamma = \frac{L_Q}{1+\gamma} \leq L_Q.$$

Define  $\mathcal{A}_\varepsilon = \{x : |p(x) - \lambda| > \varepsilon\}$ , for all  $0 < \varepsilon \leq \varepsilon_0$ . For any measurable set  $G \subset \mathcal{X} \setminus \mathcal{L}$ , we have

$$\begin{aligned} \int_G |p(x) - \lambda| dQ(x) &\geq \varepsilon Q(G \cap \mathcal{A}_\varepsilon) \\ &\geq \varepsilon [Q(G) - Q(\mathcal{A}_\varepsilon^c \cap \mathcal{L}^c)] \\ &\geq \varepsilon [Q(G) - \underline{c}\varepsilon^\gamma], \quad \forall \underline{c} > c, \end{aligned}$$

where the last inequality is obtained using (i). Maximizing the last term w.r.t  $\varepsilon > 0$ , we get

$$\left( \int_G |p(x) - \lambda| dQ(x) \right)^{\frac{\gamma}{1+\gamma}} \geq Q(G) \left( \frac{\gamma}{1+\gamma} \right)^{\frac{\gamma}{1+\gamma}} \left( \frac{1}{1+\gamma} \right)^{\frac{1}{1+\gamma}} \underline{c}^{-1/(1+\gamma)}.$$

This yields (6.1) with  $c' = e^{-2/e} \underline{c}^{1/(1+\gamma)}$ . Note that the maximum is obtained for  $\varepsilon = \left( \frac{Q(G)}{\underline{c}(1+\gamma)} \right)^{1/\gamma} \leq \varepsilon_0$  for sufficiently large  $\underline{c}$  and (i) is valid for this particular  $\varepsilon$ .

We now prove that (ii)  $\Rightarrow$  (i). Consider  $\varepsilon_1 > 0$  such that  $Q(\mathcal{A}_\varepsilon^c \cap \mathcal{L}^c) \leq L_Q$  for any  $0 < \varepsilon \leq \varepsilon_1$  and  $c' > 0$  such that (6.1) is satisfied for any  $G \subseteq \mathcal{X} \setminus \mathcal{L}$ ,  $Q(G) \leq L_Q$ . Taking  $G = \mathcal{A}_\varepsilon^c \cap \mathcal{L}^c$  in (6.1) yields

$$\begin{aligned} Q\{x : 0 < |p(x) - \lambda| \leq \varepsilon\} &= Q(\mathcal{A}_\varepsilon^c \cap \mathcal{L}^c) \\ &\leq c' \left( \int_{\mathcal{A}_\varepsilon^c \cap \mathcal{L}^c} |p(x) - \lambda| dQ(x) \right)^{\frac{\gamma}{1+\gamma}} \\ &\leq c' (\varepsilon Q(\mathcal{A}_\varepsilon^c \cap \mathcal{L}^c))^{\frac{\gamma}{1+\gamma}}. \end{aligned}$$

Therefore,

$$Q\{x : 0 < |p(x) - \lambda| \leq \varepsilon\} \leq (c')^{1+\gamma} \varepsilon^\gamma.$$

This inequality yields (i) with  $\varepsilon_0 = \varepsilon_1$  and  $c = (c')^{1+\gamma}$ . ■

## 6.2 On $\beta$ -valid kernels

We recall here the definition of  $\beta$ -valid kernels and give a property that is useful in the present study.

**Definition 6.1** *Let  $K$  be a real-valued function on  $\mathbb{R}^d$ , with support  $[-1, 1]^d$ . For fixed  $\beta > 0$ , the function  $K(\cdot)$  is said to be a  $\beta$ -valid kernel if it satisfies  $\int K = 1$ ,  $\int |K|^p < \infty$  for any  $p \geq 1$ ,  $\int \|t\|^\beta |K(t)| dt < \infty$ , and, in case  $\lfloor \beta \rfloor \geq 1$ , it satisfies  $\int t^s K(t) dt = 0$  for any  $s = (s_1, \dots, s_d) \in \mathbb{N}^d$  such that  $1 \leq s_1 + \dots + s_d \leq \lfloor \beta \rfloor$ .*

**Example 6.1** *Let  $\beta > 0$ . For any  $\beta$ -valid kernel  $K$  defined on  $\mathbb{R}^d$ , consider the following product kernel*

$$\tilde{K}(x) = K(x_1)K(x_2) \dots K(x_d) \mathbb{1}_{x \in [-1, 1]^d},$$

*for any  $x = (x_1, \dots, x_d) \in \mathbb{R}^d$ . Then it can be easily shown that  $\tilde{K}$  is a  $\beta$ -valid kernel on  $\mathbb{R}^d$ . Now, for any  $\beta > 0$ , an example of a 1-dimensional  $\beta$ -valid kernel is given in (Tsybakov, 2004a, section 1.2.2), the construction of which is based on Legendre polynomials. This eventually proves the existence of a multivariate  $\beta$ -valid kernel, for any given  $\beta > 0$ .*

The following proposition holds.

**Proposition 6.2** *Fix  $\beta > 0$ . If  $K$  is a  $\beta$ -valid kernel, then  $K$  is also a  $\beta'$ -valid kernel for any  $0 < \beta' \leq \beta$ .*

PROOF. Fix  $\beta$  and  $\beta'$  such that  $0 < \beta' \leq \beta$ . Observe that  $\lfloor \beta' \rfloor \leq \lfloor \beta \rfloor$  yields that if  $\lfloor \beta' \rfloor \geq 1$ , for any  $\beta$ -valid kernel  $K$ , we have  $\int t^s K(t) dt = 0$  for any  $s = (s_1, \dots, s_d)$  such that  $1 \leq s_1 + \dots + s_d \leq \lfloor \beta' \rfloor$ . It remains to check that

$$\int_{\mathbb{R}^d} \|t\|^{\beta'} |K(t)| dt < \infty. \quad (6.2)$$

Consider the decomposition

$$\begin{aligned} \int_{\mathbb{R}^d} \|t\|^{\beta'} |K(t)| dt &= \int_{\|t\| \leq 1} \|t\|^{\beta'} |K(t)| dt + \int_{\|t\| \geq 1} \|t\|^{\beta'} |K(t)| dt \\ &\leq \int_{\mathbb{R}^d} |K(t)| dt + \int_{\|t\| \geq 1} \|t\|^{\beta} |K(t)| dt. \end{aligned}$$

To prove (6.2), remark that since  $K$  is a  $\beta$ -valid kernel, we have  $\int_{\mathbb{R}^d} |K(t)| dt < \infty$  and

$$\int_{\|t\| \geq 1} \|t\|^{\beta} |K(t)| dt \leq \int_{\mathbb{R}^d} \|t\|^{\beta} |K(t)| dt < \infty.$$

■

### 6.3 Technical lemmas for minimax lower bounds

We gather here technical results that are used in Section 5. For a recent survey on the construction of minimax lower bounds, see Tsybakov (2004a)[Chap. 2]. We first give a lemma related to subset extraction.

Fix an integer  $m \geq 1$ , and for any two  $\omega = (\omega_1, \dots, \omega_m)$  and  $\omega' = (\omega'_1, \dots, \omega'_m)$  in  $\{-1, 1\}^m$  define the *Hamming distance* between  $\omega$  and  $\omega'$  by

$$\rho(\omega, \omega') = \sum_{i=1}^m \mathbb{I}_{\{\omega_i \neq \omega'_i\}}.$$

The following lemma holds.

**Lemma 6.1 (Varshamov-Gilbert bound, 1962)** *Fix  $m \geq 8$ . Then there exists a subset  $\Omega = \{\omega^{(0)}, \dots, \omega^{(M)}\}$  of  $\{-1, 1\}^m$  such that  $M \geq 2^{m/8}$  and*

$$\rho(\omega^{(j)}, \omega^{(k)}) \geq \frac{m}{8}, \quad \forall 0 \leq j < k \leq M.$$

For a proof of this lemma, see Tsybakov (2004a, Lemma 2.8, p. 89).

The next lemma can be found in Tsybakov (2004a, Theorem 2.5, p. 85) and is stated here in a form adapted to our purposes. It allows to derive



minimax lower bounds in the context of DLSE. It involves the Kullback-Leibler divergence between two probability densities  $p$  and  $q$  on  $\mathbb{R}^d$

$$K(p, q) = \begin{cases} \int_{\mathbb{R}^d} \log \left( \frac{p(x)}{q(x)} \right) p(x) dx & \text{if } P_p \ll P_q, \\ +\infty & \text{else.} \end{cases}$$

**Lemma 6.2** *Let  $d$  be a pseudo-metric between subsets of  $\mathcal{X} \subset \mathbb{R}^d$ . Let  $\mathcal{P}$  be a set of densities and assume that there exists a finite subset  $\mathcal{N} \subset \mathcal{P}$  with  $2 \leq \text{card}(\mathcal{N}) = s < \infty$  and a constant  $C > 0$ , such that*

$$d(\Gamma_p(\lambda), \Gamma_q(\lambda)) \geq 2\varepsilon, \quad \forall p, q \in \mathcal{N}, p \neq q, \quad (6.3)$$

*and there exists  $p \in \mathcal{N}$  such that*

$$\max_{q \in \mathcal{N}} K(q, p) \leq C \log(s). \quad (6.4)$$

*Then, there exists an absolute positive constant  $C'$  such that for any estimator  $\hat{G}_n$  of  $\Gamma_p(\lambda)$  constructed from the sample  $X_1, \dots, X_n$ , we have*

$$\sup_{p \in \mathcal{P}} \mathbb{E} \left[ d(\Gamma_p(\lambda), \hat{G}_n) \right] \geq C' \varepsilon.$$

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